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**Monitoring of Liquid Sprayed Conical Spouted Beds by Recurrence Plots**

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**Abstract**

In this study, the chaotic behavior of gas-solid flow in a laboratory scale conical spouted bed during spraying of water on the sugar particles was investigated using non-linear analyses of pressure fluctuations (PFs) and acoustic emission (AE) signals. The phase space trajectories, recurrence plots (RP) and recurrence quantification analyses (RQA), as powerful non-linear techniques, were used for monitoring of the bed hydrodynamics. It was concluded that the reconstructed phase space trajectories of both PFs and AE signals approach to a slim and elongated patterns with the formation of agglomerates due to injection of water into the bed. Examinations of the RP maps show that the contribution of patches with larger distances increases by an increase of water content in the bed. Moreover, the RQA results show that the maximum length of diagonal lines of RPs increases by injection of the water into the bed showing that the hydrodynamic status of the bed becomes more deterministic. The results of this work show the high potential of these methods for proper understanding of the hydrodynamics of spouted beds with liquid injection and associated agglomeration phenomenon.

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**Keywords:** conical spouted bed, pressure fluctuation, acoustic emission, recurrence plot, hydrodynamic monitoring

## 1. Introduction

Conical spouted beds are gas-solid contactors successfully employed in numerous industrial processes such as gasification, combustion, granulation, coating and drying of suspensions, solutions, and pastry materials [1-3]. These beds show good particle mixing and liquids can be easily sprayed into the bed through a nozzle placed at top or bottom [1]. Coating and granulation processes usually involve the presence of a liquid in the bed. The addition of liquid leads to an increase in particle cohesiveness and promotes de-spouting and bed malfunctioning in some cases. Therefore, the hydrodynamics of a spouted bed may change over time due to instabilities, such as intense oscillation in fountain height, vigorous swings of the spout from side to side, choking and consequent slugging of the spout imposed by particle size changes and cohesiveness. Since the performance of liquid sprayed conical spouted beds strongly depends on their hydrodynamics status, their monitoring is crucial to control the product quality [4].

There are many measurement techniques to determine the hydrodynamic properties of spouted beds, such as pressure fluctuations (PFs) [5-7], fiber optic (FO) [8, 9], radioactive particle tracking (RPT) [10], capacitance tomography (CT) [11, 12], computer-based video imaging [13, 14] and acoustic emission (AE) signals [15]. Since pressure fluctuations are easily measurable and include effects of different dynamic phenomena taking place in the bed, such as individual and bulk movement of particles and formation and movement of agglomerates [16], many researchers have used pressure fluctuations for characterization of

the system [5-7, 16]. Since it is necessary to insert the pressure probe into the bed through an orifice, this measurement technique has some limitations at severe, corrosive and high pressure/temperature conditions. Furthermore, some other measurement problems might appear, such as blockage of the probe by solids [17]. Consequently, the need for developing other non-invasive monitoring techniques is clear. Recently, acoustic emission measurement technique has gained attention as it is a non-invasive, low cost, reliable measurement technique and applicable to a wide range of process conditions [18]. This technique has a potential to improve process understanding and to provide a basis for on-line monitoring and control of various processes. However, there are only two studies in the open literature on monitoring of AE signals in spouted beds [15, 19]. Therefore, investigating the adoption of AE signals for monitoring the hydrodynamic status of spouted beds and its comparison with other known techniques, such as PF measurements, seems to be necessary.

Standard methods in time series analysis include statistical (e.g., standard deviation, skewness and kurtosis) or spectral analysis (e.g., fast Fourier transform, power spectrum). A proper understanding of the state of complex systems cannot be determined by linear methods in time and frequency domains. Various nonlinear analysis techniques, such as short-term predictability and attractor comparison, have been used for analyzing the dynamics of complex systems [20]. These nonlinear techniques are based on reconstruction of an attractor of dynamic evaluation of the system and allow extracting useful information about its dynamical state. However, these methods have some limitations, such as long term data sampling requirement, time consuming numerical calculations and uncertainty in the determination of embedding parameters [20, 21].

In this study, a monitoring technique based on the recently introduced nonlinear analysis method of recurrence plot (RP) and recurrence quantification analysis (RQA) [22] of PFs and AE signals is developed for the detection of changes in hydrodynamics of a liquid sprayed conical spouted bed. The main advantageous feature of the RP is that a high-dimensional dynamical system, whose state space trajectory is difficult to visualize, can be represented in a two-dimensional plot. Another considerable characteristic of the RP analysis is that it provides useful information using a non-stationary and short-term data. In other words, difficulties associated with typical nonlinear analysis methods, such as long-term data samplings and time consuming algorithms, can be avoided when using the RP method. Although nonlinear analysis by RP has been used in the characterization of fluidized bed hydrodynamics [23-25], oil-water two phase flow [26, 27], gas-liquid two phase flow [28], bubble and rimming flows [29, 30], application of this method to spouted beds is rare [31]. Therefore, in this study, in order to determine the hydrodynamic state, two kinds of recurrence plots (thresholded RP and unthresholded RP) and an RQA parameter (maximal length of diagonal line) of both pressure fluctuations and acoustic emission signals were obtained from a conical spouted bed and analyzed.

## 2. Experimental method

The experimental data were obtained in a full circular conical spouted bed of diameter 150 mm with a conical base of internal angle  $45^\circ$  and an inlet orifice diameter of 6 mm. A schematic diagram of the bed with bottom liquid spray is shown in Fig. 1. The spouting gas flow rate was supplied from a screw type air compressor operating with a supply pressure of 8 bar at a maximum flow rate of  $0.05 \text{ m}^3/\text{s}$ . A pressure regulator and an air tank of 30 L in volume were placed between the supply line and the spouted bed gas inlet to eliminate air

flow rate fluctuations. Tap water was sprayed into the bed with a nozzle positioned at the center of the air inlet orifice.

High speed camera photography was employed in a half column conical spouted bed for visualizing the flow patterns during water injection and drying periods. The half bed was simply sliced full column with a flat Plexiglas sheet attached to the front open surface for visual observation and photography. Both full and half beds had the same geometrical dimensions. Images were acquired with a camera (UI-2210SE, IDS Co.) equipped with a 16 mm PENTAX lens having a resolution of  $640 \times 480$  pixels with the frame rate up to 200 frame/s (fps).

Differential pressure transducer (PX163-120D5V, OMEGA Engineering) connected to a 16 bit data acquisition board (National Instruments, USB-6351) was used to record PFs time series. The measuring port of the pressure transducer was connected to the base of conical section of the bed, as shown in Fig. 1, while the other port of the pressure transducer was left open to the atmosphere. The PFs time series were recorded at a sampling frequency of 500 Hz. The AE signals were measured by an omnidirectional back electret condenser microphone (Panasonic, WM-61 A) which had a frequency response of 0.02-20 kHz (sensitivity:  $-35 \pm 4$  dB, signal to noise ratio: more than 62 dB). The outlet signal from the microphone was recorded by a USB interface sound analyzer (ARTIMAN Instruments, ART-SA16) with a sampling frequency of 44 kHz. The AE sensor was installed by silicon grease externally to the outer surface of the bed at 120 mm above the base of the conical section. Location of the acoustic sensor was selected based on the findings of Oliveria et al. [15] who showed the similarity of AE signals measured at different positions.

PFs and AE signals were recorded continuously during the spraying of water on the sugar particles having 720  $\mu\text{m}$  mean diameter and density of 1580  $\text{kg/m}^3$ . In the experiments, water was sprayed every 2 minutes into the bed with a flow rate of 3 mL/min for 10 seconds until the bed collapsed. In order to compare the signals during water injection with the ones measured in the dry bed, the PFs and AE signal measurements were started 2 minutes prior to the first water injection interval. The static bed height and ratio of the inlet gas velocity to minimum spouting gas velocity ( $U/U_{ms}$ ) were maintained constant at 120 mm and 1.2, respectively. To eliminate possible effects of the initial packing status on the measurements, the bed was spouted for 10 minutes prior to spraying of water in each experiment. Visual observation of the bed hydrodynamics was performed in order to characterize the bed behavior during experiments.

### 3. Theory

#### 3.1. Recurrence Plots

Recurrence plot visualizes recurrences in the dynamics of a dynamical system [22]. In literature there are several variations of recurrence plots. Thresholded recurrence plot (TRP), is a widely used kind of recurrence plot that represents repeated states of a phase space of the system. The TRP is a two-dimensional squared matrix,  $R$ , which is mathematically expressed as [32]:

$$R_{i,j} = \theta(\varepsilon - \|\vec{x}_i - \vec{x}_j\|) \quad i, j = 1, 2, 3, \dots, N \quad (1)$$

where  $N$  is the number of state space points,  $\vec{x}_i, \vec{x}_j \in R^m$  are  $i$ -th and  $j$ -th points of the  $m$ -dimensional state space trajectory,  $\varepsilon$  is a threshold distance,  $\|\cdot\|$  is the norm and  $\theta$  is the



Heaviside function. In fact, the matrix  $R$  compares the states of a system at times  $i$  and  $j$ . If the states are similar (the norm is less than  $\varepsilon$ ), this would be marked by a 1 in the matrix, i.e.,  $R_{i,j}=1$ , and a black spot would appear on the plot at coordinate  $(i, j)$ . If, on the other hand,  $\vec{x}_i$  and  $\vec{x}_j$  are rather different (the norm is greater than  $\varepsilon$ ), the corresponding entry in the matrix would be  $R_{i,j} = 0$  and a white spot would appear on the plot. In other words, this matrix can tell when similar states of the underlying system have occurred.

Unthresholded recurrence plot (UTRP) can be defined based on the distance matrix [32]:

$$D_{i,j} = \|\vec{x}_i - \vec{x}_j\| \quad (2)$$

This type of recurrence plot is defined as the closeness of the state  $\vec{x}_i$  to the state  $\vec{x}_j$ . UTRPs show the distance among all points in the state space via a color map while TRPs highlight only those points that fall within the radius threshold ( $\varepsilon$ ). The radius threshold is a crucial parameter in visual comparison of TRPs, but UTRP eliminates the need to have a threshold distance. Small variations in the distances between points can be detected by UTRP maps, while these variations cannot be detected in TRPs, if the variation is less than the predefined cut-off distance. Therefore, the patterns in a UTRP are more informative. On the other hand, it is more difficult to quantify the patterns in a UTRP compared to those in a TRP. Thus, in the present work, the UTRPs were used for visual inspection of RPs whereas the TRPs were applied for recurrence quantification analysis of the time series.

### 3.2. Recurrence Quantification Analysis

Several methods have been proposed for quantifying the complexity of structures in TRPs [32-35]. Small scale structures are the base of a quantitative analysis which is known as recurrence quantification analyses, RQA. Several recurrence quantification parameters, such

as recurrence rate, determinism, laminarity and entropy, have already been examined for detection of agglomeration in conical spouted beds in a previous study [19]. In the present study, changes of  $L_{max}$  (length of the longest diagonal line in the TRP, excluding the main diagonal line) were investigated during the water spraying process.  $L_{max}$  is an important recurrence variable because its inverse is related to the Lyapunov exponent [32]. Positive Lyapunov exponents hint the rate at which trajectories diverge. Thus, the shorter the  $L_{max}$ , the more divergent are the trajectories and the more chaotic is the signal. Many researchers have demonstrated that  $L_{max}$  can be a useful index to survey the attractor comparisons [33-35]. Thus, this parameter was used as a quantitative measure for comparing PF and AE trajectories in this study.

#### 4. Results and Discussion

Behavior of a chaotic system can be analyzed based on the trajectories of reconstructed attractors in the phase space. For visual comparison of reconstructed attractor trajectories, 2 and 3-dimensional phase space ( $m = 2$  and  $m = 3$ ) are often used [36, 37]. Here for better visualization of the reconstructed attractors,  $m = 3$  has been selected for phase space embedding dimension. The attractor reconstruction is also a function of time delay ( $\tau$ ). The mutual information function between time series of  $x(t)$  and  $x(t + \tau)$  is a general guidance to determine proper time delay. The common way of selecting a proper time delay includes finding the first minimum in the mutual information function of the time series [32, 38]. In this study, the changing tendency of mutual information function according to the time delay showed that the first minimum of mutual information function of both PFs and AE signals happen at  $\tau = 1$ . It was interesting to observe that for  $\tau = 1$  the points of reconstructed attractors were close to diagonal indicating that the time delay was too small for an

appropriate reconstruction. In order to define  $\tau$  properly in the present work, the attractors of PFs and AE signals of the dry bed were reconstructed with different values of time delay, chosen around those suggested by the mutual information function ( $\tau = 1$  to 10). It was found that reconstructed attractors of PFs and AE signals did not change significantly for  $\tau \geq 4$ . On the other hand, when the attractors were reconstructed with  $\tau = 4$ , the points were close to each other, forming a circular shape (shown in Fig. 2a), indicating that a good reconstruction was performed. Therefore, the proper time delay was taken to be 4 in this study. Fig. 2 shows reconstructed 3-dimensional ( $m = 3$ ) attractors from time-delayed values of PFs and AE signals at different water content of the bed. As can be seen from Fig. 2a, the points of attractors are dispersed all over the phase space plot, forming a circular shape. The attractors of PFs and AE signals become less scattered with increasing water content of the bed (Fig. 2b and c). The attractors shown in Fig. 2c are slim and have an elongated pattern. The elongated pattern of the PFs attractor is due to occurrence of large peaks in the signal as a result of extreme pulsation of the bed. Meanwhile, the relative distance between other points located in two poles of this attractor has not changed considerably. In other words, only a peak has occurred in the PFs, causing points of the attractor to become divided in two groups while the relative position of the points in each group has not changed significantly. On the other hand, while this separation of points did not appear in the AE attractor, the relative distance of all points in this was changed by water injection.

Sample UTRPs of PFs and AE signals obtained at various water content of the bed are shown in Fig. 3 for  $\tau = 4$  and  $m = 3$ . In the given UTRPs, the pixels of the plot are colored depending on the magnitude of the distance,  $D_{ij}$  where blue and green pixels represent states (micro-states) that are close to each other in the reconstructed phase space, yellow pixels correspond

to intermediate distances and red pixels represent states (macro-states) with larger distances. In this analysis, micro-states refer to the particle-particle, particle-fluid and particle-wall interactions while macro-states reflect bulk movement of solids and fluid-solid bulk interactions. A first qualitative conclusion that can be drawn from Figs. 3a-c is that the UTRPs of PFs and AE signals are more homogeneous (in color) for dry bed. As water is sprayed into the bed, the color homogeneity of UTRPs is gradually lost and contribution of yellow and red patches (colors correspond to larger distances) increase.

Fig. 4 demonstrates photos of the spouted bed for various amount of water sprayed into the bed at  $U/U_{ms} = 1.2$ . In these tests, the black ink was added to the spraying water for better observation of the flow. As can be seen in Fig.4a, dry particles form a stable spout in the bed with small oscillations in the fountain height. Particles are carried by the gas flow in the center of the bed and move downward in the annulus region. The movement of particles is smooth, while the spout and fountain is stable and non-pulsating. This stable spout generates PFs and AE signals with homogenous UTRPs (Fig.3a). When water is sprayed into the bed, some instabilities are observed. With the injection of water, the fountain height oscillates more vigorously and the bed shows extreme pulsations (Figs.4c and d). The particles are more likely to be carried in the spout as agglomerates than individually. These extreme pulsations in the bed produce PFs and AE signals with relatively higher amplitude which results in the appearance of yellow and red patches in the UTRPs. The adhesion tendency of particles intensifies with further spraying of water and, eventually, the gas flow rate ceases to be sufficient to keep a stable spouting regime leading to bed collapse.

Another qualitative conclusion that can be drawn from Figs. 3a-c is that in contrast to UTRPs of PFs, changes in the visual appearance of the UTRPs of AE signals are more obvious, even without any quantification analysis. This reveals that large scale appearance and typology of UTRPs of AE signals can be easily used to monitor the hydrodynamics of spouted beds. Therefore, it can be concluded that although UTRPs of both PFs and AE signals are responsive to hydrodynamic changes in the spouted bed, UTRPs of AE signals is substantially more sensitive to these changes. In other words, detection of slight hydrodynamic changes of the bed can be detected more accurately by UTRPs of the AE signals.

More information can be drawn from UTRPs of PFs and AE signals by zooming on the sub-regions of these plots. Figs. 5a-c show samples of magnified sub-regions of UTRPs of PFs and AE signals. In case of PFs, there are many vertical and horizontal lines formed mainly by blue points (smaller distances). The horizontal and vertical lines indicate the states that do not change or change slowly. This demonstrates that laminar states are abundant in PFs of spouted beds. On the other hand, contribution of diagonal lines and regular structures is greater in UTRPs of AE signals. This indicates that AE signals of spouted bed are more deterministic than PFs. The AE signal in a spouted bed mainly originates from particle-particle and particle-wall collisions at the surface of annulus and the fountain region while PFs mainly reflect single and bulk motion and gas-particle interactions, which are more chaotic at the base of the spout than at the bed surface. Therefore, RP of AE signals contains more diagonal lines compared to that of PFs. Moreover, variations in the colors of magnified UTRPs of AE signals of the spouted bed with the increase in water content is more visible

compared to the original AE-UTRPs (Figs. 3a-c) which suggest the high potential of such monitoring method for the hydrodynamics of spouted beds.

As discussed above, the visual inspection of UTRP maps and their variations can be used for monitoring the hydrodynamic changes of spouted beds during water injection. However, precise monitoring of changes in the bed hydrodynamics needs quantitative analyses. In this study, the TRPs were quantified by the RQA in terms of maximal length of diagonal line,  $L_{max}$ . For this purpose, the measured PFs and AE signals were partitioned into smaller windows or epochs (4000 points for PFs and 4400 points for AE signal) and  $L_{max}$  was calculated for each window. Offset for adjacent windows was set to 4 seconds, meaning that each window was shifted for 4 seconds over the main signal. It should be noted that in the experiments, a gradual decrease of the fountain height was observed with the injection of water. A point was then reached where a sudden collapse of the spout was observed, leading to the complete cessation of spouting. The time it took for the complete cessation of spouting from the beginning of water injection was 8.5 minutes at  $U/U_{ms}=1.2$ . Fig. 6 illustrates variations of  $L_{max}$  of PFs and AE signals during water injection process. In this figure, a 3<sup>rd</sup> degree polynomial trend line is drawn through each data set. As can be seen in Fig. 6,  $L_{max}$  of PFs and AE signals were stable for dry bed (during the first 2 minutes, before start of water injection) and increased during water spraying process (after the 2 minutes). As mentioned previously,  $L_{max}$  is a hint about the divergence rate of the trajectory segments. The increasing trend of  $L_{max}$  indicates that the divergence rate of the reconstructed attractor trajectories of PFs and AE signals reduces with the increase in the water content of the bed. These trends show that signal pattern approaches to the characteristics of a periodic time series when water is sprayed into the bed. In fact, it is thought that after spraying of enough water into the bed,

the wet particles in contact with each other form liquid bridges that, after water evaporation, consolidate into solid bridge, causing formation of particle agglomerates. Thus, the contribution of bulk movement of particles and agglomerates to the associated signal increases with an increase of water content. Therefore, it can be concluded that hydrodynamic characteristics of bulk solids and agglomerates are more deterministic than the movement of single particles. Results concerning  $L_{max}$  show that maximum diagonal line length of PFs and AE signals can be interpreted as a good and early enough indicator for small changes in hydrodynamics of spouted bed when water is sprayed into the bed.

## 5. Conclusion

The pressure fluctuations (PFs) and acoustic emission (AE) signals of a bottom sprayed conical spouted bed with sugar particles were obtained at an inlet gas velocity of  $1.2U_{ms}$ . These measured time series were analyzed using non-linear phase space trajectories, unthresholded and thresholded recurrence plots (RP) and recurrence quantification analysis (RQA). The reconstructed phase space trajectories of both PFs and AE signals approach to a slim and elongated pattern by injection of water into the bed. This trend was confirmed by unthresholded recurrence plots (UTRPs) of PFs and AE signals obtained at various times of agglomeration tests too, since at higher contents of water, the contribution of bulk movement of particles and agglomerates to the associated signal increases. Moreover, examination of maximum length of diagonal lines of thresholded RPs (TRPs) showed that PFs and AE signals of the bed approach that of a periodic time series with the increase of the amount of water. Therefore, it can be concluded that hydrodynamic behavior of bulk movement and agglomerates is more deterministic than movement of single particles. The results of the

presented work showed that RP and RQA is a powerful technique for monitoring of hydrodynamic behavior of spouted beds.

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### Nomenclature

$D_c$	column diameter (mm)
$D_{i,j}$	elements of distance matrix
$D_i$	cone bottom diameter (mm)
$D_o$	gas inlet diameter (mm)
$H_b$	static bed height (mm)
$H_c$	height of conical section (mm)
$L_{max}$	maximal length of diagonal line
$m$	embedding dimension
$N$	number of time series points
$R_{i,j}$	recurrence plot matrix



$U$	inlet gas velocity (m/s)
$U_{ms}$	minimums spouting velocity, m/s
$\vec{x}_i$	$i$ -th point of state space trajectory
<i>Greek letters</i>	
$\Theta$	Heaviside function
$\gamma$	cone angle
$\varepsilon$	radius threshold
$\tau$	time delay vector

## References

- [1] N. Epstein, J.R. Grace, *Spouted and Spout-fluid Beds: Fundamentals and Applications*, Cambridge University Press, Cambridge, 2010.
- [2] P.K. Mollick, D. Sathiyamoorthy, Assessment of stability of spouted bed using pressure fluctuation analysis, *Ind. Eng. Chem. Res.* 51 (2012) 12117-12125.
- [3] C.C. Huang, H.O. Kono, Granulation and rehydration of rehydratable alumina powders, *Ind. Eng. Chem. Res.* 28 (1989) 910-919.
- [4] M.J. San José, M. Olazar, S. Alvarez, J. Bilbao, Local bed voidage in conical spouted beds, *Ind. Eng. Chem. Res.* 37 (1998) 2553-2558.
- [5] W. Oliveira, C. Souza, C. Lim, J. Grace, Evaluation of flow regimes in a semi-cylindrical spouted bed through statistical, mutual information, spectral and Hurst's analysis, *Can. J. Chem. Eng.* 86 (2008) 582-597.
- [6] J. Xu, X. Bao, W. Wei, H.T. Bi, J.R. Grace, C.J. Lim, Chaotic characteristics of pressure fluctuations in a gas spouted bed, *Can. J. Chem. Eng.* 87 (2009) 252-263.
- [7] W. Zhong, M. Zhang, Characterization of dynamic behavior of a spout-fluid bed with Shannon entropy analysis, *Powder Technol.* 159 (2005) 121-126.
- [8] M. Olazar, M.J. San Jose, R. LLamosas, S. Alvarez, J. Bilbao, Study of local properties in conical spouted beds using an optical fiber probe, *Ind. Eng. Chem. Res.* 34 (1995) 4033-4039.
- [9] M. Olazar, M.J. San José, S. Alvarez, A. Morales, J. Bilbao, Measurement of particle velocities in conical spouted beds using an optical fiber probe, *Ind. Eng. Chem. Res.* 37 (1998) 4520-4527.

- [10] L. Spreutels, B. Haut, R. Legros, F. Bertrand, J. Chaouki, Experimental investigation of solid particles flow in a conical spouted bed using radioactive particle tracking, *AIChE J.* 62 (2016) 26-37.
- [11] R. Ge, J. Ye, H. Wang, W. Yang, Measurement of particle concentration in a Wurster fluidized bed by electrical capacitance tomography sensors, *AIChE J.* 60 (2014) 4051-4064.
- [12] M. Takei, T. Zhao, K. Yamane, Measurement of particle concentration in powder coating process using capacitance computed tomography and wavelet analysis, *Powder Technol.* 193 (2009) 93-100.
- [13] X.L. Zhao, S.Q. Li, G.Q. Liu, Q. Yao, J.S. Marshall, DEM simulation of the particle dynamics in two-dimensional spouted beds, *Powder Technol.* 184 (2008) 205-213.
- [14] G.Q. Liu, S.Q. Li, X.L. Zhao, Q. Yao, Experimental studies of particle flow dynamics in a two-dimensional spouted bed, *Chem. Eng. Sci.* 63 (2008) 1131-1141.
- [15] W. Oliveira, J. Grace, C. Lim, M. Hodgson, Investigation of acoustic signals as a tool for characterizing spouted bed dynamics, *Can. J. Chem. Eng.* 87 (2009) 298-307.
- [16] N. Mostoufi, G. Kulah, M. Koksai, Flow structure characterization in conical spouted beds using pressure fluctuation signals, *Powder Technol.* 269 (2015) 392-400.
- [17] J.R. van Ommen, J.C. Schouten, M.L. vander Stappen, C.M. van den Bleek, Response characteristics of probe-transducer systems for pressure measurements in gas-solid fluidized beds: how to prevent pitfalls in dynamic pressure measurements, *Powder Technol.* 106 (1999) 199-218.
- [18] J.W. Boyd, J. Varley, The uses of passive measurement of acoustic emissions from chemical engineering processes, *Chem. Eng. Sci.* 56 (2001) 1749-1767.

- [19] C. Savari, G. Kulah, R. Sotudeh-Gharebagh, N. Mostoufi, M. Koksai, Early Detection of Agglomeration in Conical Spouted Beds Using Recurrence Plots, *Ind. Eng. Chem. Res.* 55 (2016) 7179-7190.
- [20] R. Zarghami, N. Mostoufi, R. Sotudeh-Gharebagh, Nonlinear characterization of pressure fluctuations in fluidized beds, *Ind. Eng. Chem. Res.* 47 (2008) 9497-9507.
- [21] C. Savari, R. Sotudeh-Gharebagh, R. Zarghami, N. Mostoufi, Non-Intrusive Characterization of Particle Size Changes in Fluidized Beds Using Recurrence Plots, *AIChE J.* 62 (2016) 3547-3561.
- [22] J.P. Eckmann, S.O. Kamphorst, D. Ruelle, Recurrence plots of dynamical systems, *Europhys. Lett.* 4 (1987) 973-977.
- [23] B. Babaei, R. Zarghami, H. Sedighikamal, R. Sotudeh-Gharebagh, N. Mostoufi, Investigating the hydrodynamics of gas–solid bubbling fluidization using recurrence plot, *Adv. Powder Technol.* 23 (2012) 380-386.
- [24] M. Tahmasebpour, R. Zarghami, R. Sotudeh-Gharebagh, N. Mostoufi, Characterization of various structures in gas-solid fluidized beds by recurrence quantification analysis, *Particuology*, 11 (2013) 647-656.
- [25] M. Tahmasebpour, R. Zarghami, R. Sotudeh-Gharebagh, N. Mostoufi, Characterization of fluidized beds hydrodynamics by recurrence quantification analysis and wavelet transform, *Int. J. Multiphase Flow*, 69 (2015) 31-41.
- [26] N.D. Jin, G.B. Zheng, F. Dong, W.P. Chen, Application of chaotic recurrence plot analysis to identification of oil-water two phase flow patterns, In: *Third International Conference on Fuzzy Systems and Knowledge Discovery*, Xi'an, RP China, 2006, pp. 1213-1216.

- [27] Y.B. Zhong, N.D. Jin, Z.Y. Wang, Z.K. Gao, C. Wang, Nonlinear dynamic analysis of large diameter inclined oil-water two phase flow pattern , *Int. J. Multiphase Flow*. 36 (2010) 166-183.
- [28] M. Du, N.D. Jin, Z.K. Gao, Analysis of total energy and time-frequency entropy of gas-liquid two phase flow pattern, *Chem. Eng. Sci.* 82 (2012) 144-158.
- [29] A. Vazquez, R. Manasseh, R. Sánchez, G. Metcalfe, Experimental comparison between acoustic and pressure signals from a bubbling flow, *Chem. Eng. Sci.* 63 (2008) 5860-5869.
- [30] R. Chicharro, A. Vazquez, R. Manasseh, Characterization of patterns in rimming flow, *Exp. Therm. Fluid Sci.* 35 (2011) 1184-1192.
- [31] C. Wang, Z. Zhong, E. Jiaqiang, Flow regime recognition in spouted bed based on recurrence plot method, *Powder Technol.* 219 (2012) 20-28.
- [32] N. Marwan, M.C. Romano, M. Thiel, J. Kurths, Recurrence plots for the analysis of complex systems, *Phys. Rep.* 438 (2007) 237-329.
- [33] N. Marwan, N. Wessel, U. Meyerfeldt, A. Schirdewan, J. Kurths, Recurrence-plot-based measures of complexity and their application to heart-rate-variability data, *Phys. Rev. E.* 66 (2002) 026702.
- [34] C.L. Webber, J.P. Zbilut, Dynamical assessment of physiological systems and states using recurrence plot strategies, *J. Appl. Physiol.* 76 (1994) 965-973.
- [35] C.L. Webber Jr, J.P. Zbilut, Recurrence Quantification Analysis of Nonlinear Dynamical Systems, *Tutorials in Contemporary Nonlinear Methods for the Behavioral Sciences*, 2005, pp. 26-94.
- [36] R. Mosdorf, P. Cheng, H. Wu, M. Shoji, Non-linear analyses of flow boiling in microchannels, *Int. J. Heat. Mass. Tran.* 48 (2005) 4667-4683.

- [37] S. Wang, R. Mosdorf, M. Shoji, Nonlinear analysis on fluctuation feature of two-phase flow through a T-junction, *Int. J. Heat. Mass. Tran.* 46 (2003) 1519-1528.
- [38] A.M. Fraser, H.L. Swinney, Independent coordinates for strange attractors from mutual information, *Phys. Rev. A.* 33 (1986) 1134.

## Figure Captions

**Fig. 1.** Schematic of conical spouted bed.

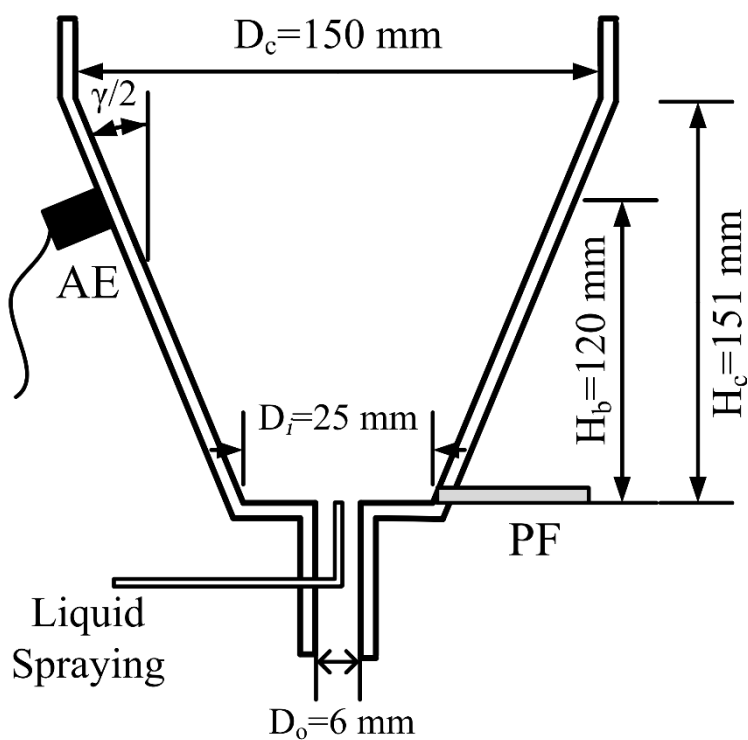
**Fig. 2.** Reconstructed attractors of PFs (left) and AE (right) signals at (a) dry bed, (b) after 0.5 mL and (c) after 1.5 mL of water injection ( $m = 3$ ,  $\tau = 4$ ).

**Fig. 3.** UTRPs of PFs (left) and AE (right) signals at (a) dry bed, (b) after 0.5 mL and (c) after 1.5 mL of water injection ( $m = 3$ ,  $\tau = 4$ ).

**Fig. 4.** Camera images of half bed during water (with black ink) injection, (a) dry bed, (b) start of water injection, (c) and (d) unstable spouting

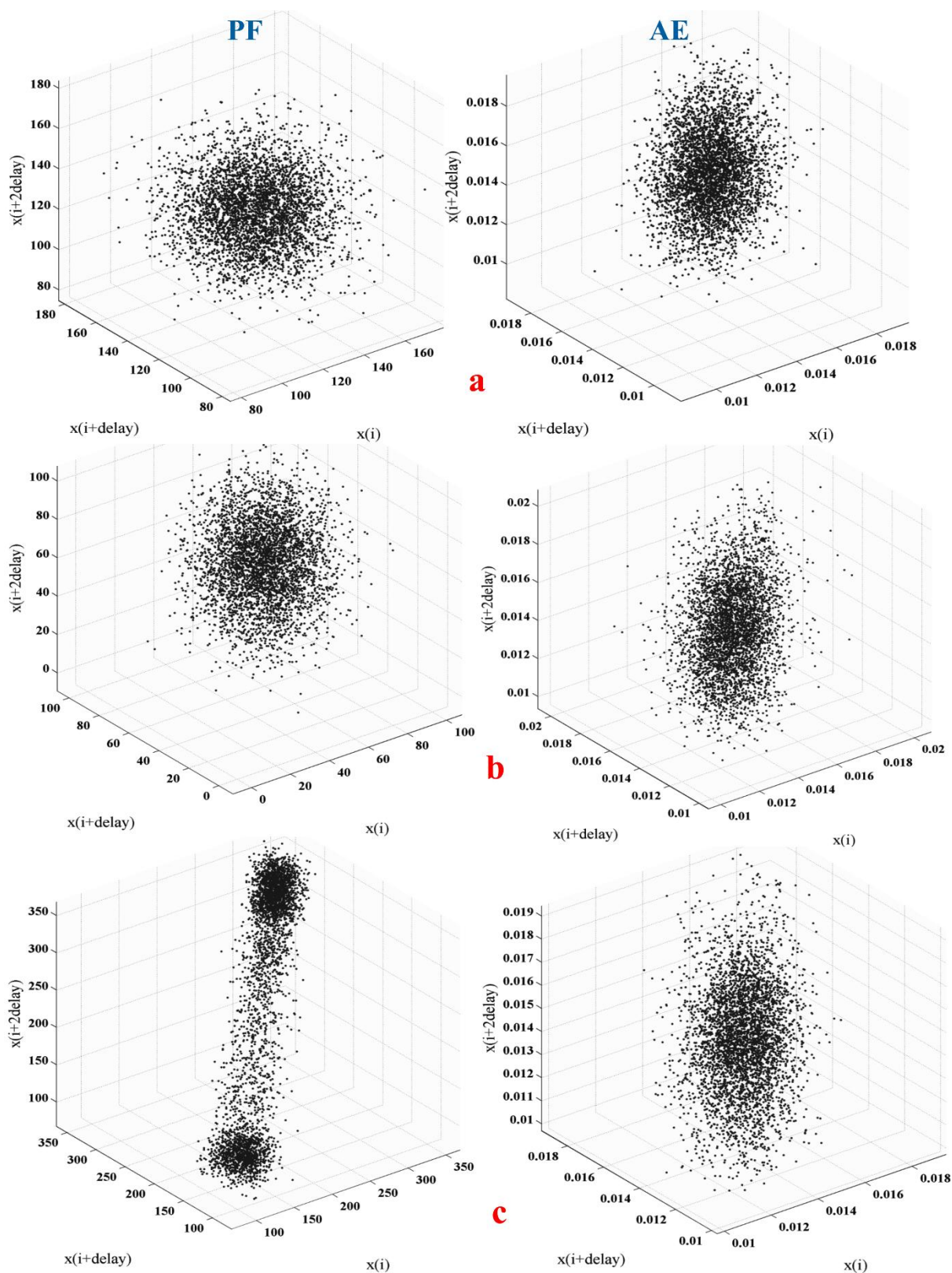
**Fig. 5.** Zoom of UTRPs of PFs (left) and AE (right) signals at (a) dry bed, (b) after 0.5 mL and (c) after 1.5 mL of water injection ( $m = 3$ ,  $\tau = 4$ ).

**Fig. 6.** Maximal length of diagonal line of the TRPs with time for PFs and AE signals.

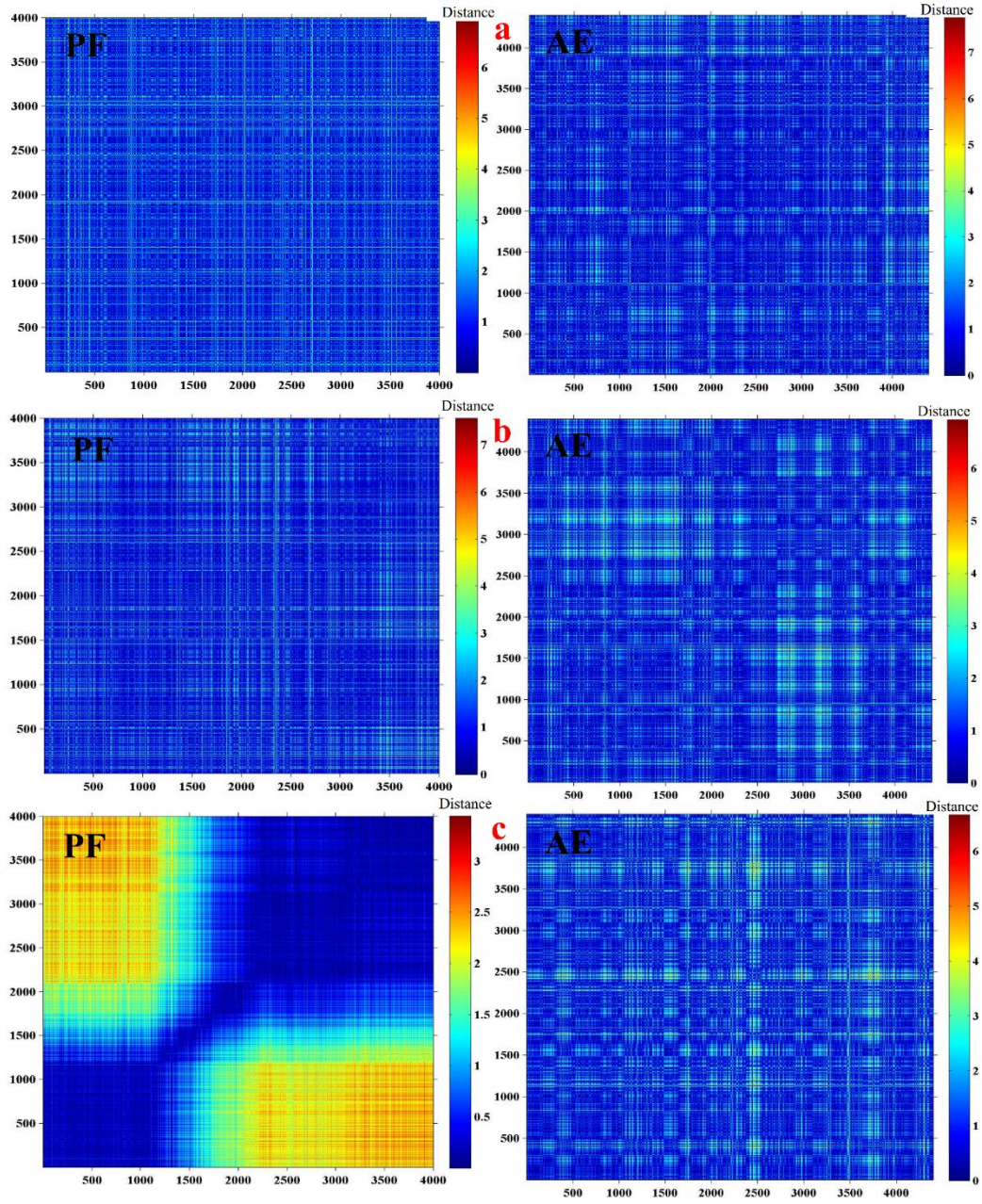


**Fig. 1.** Schematic of conical spouted bed.



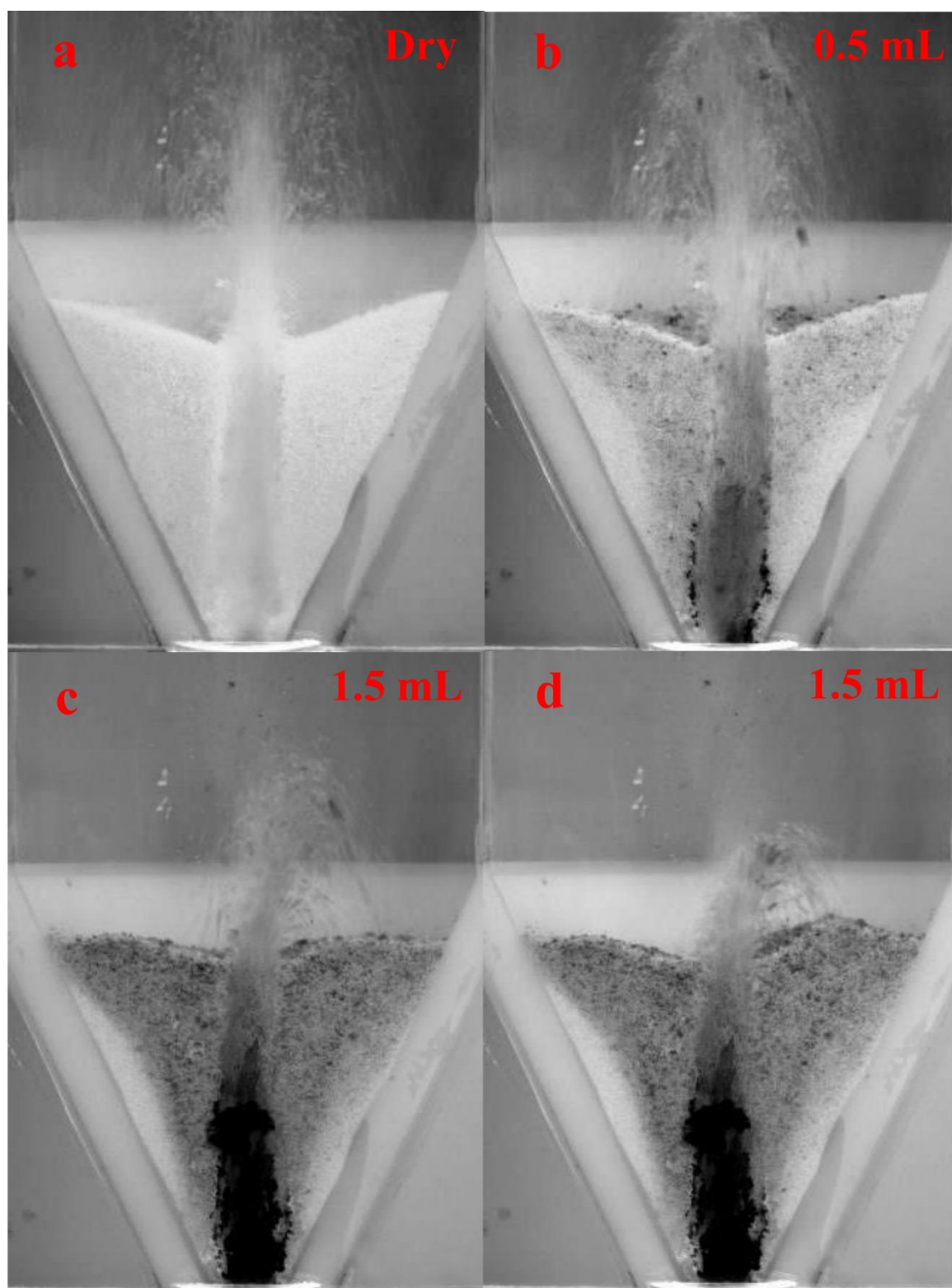


**Fig. 2.** Reconstructed attractors of PFs (left) and AE (right) signals at (a) dry bed, (b) after 0.5 mL and (c) after 1.5 mL of water injection ( $m = 3$ ,  $\tau = 4$ ).

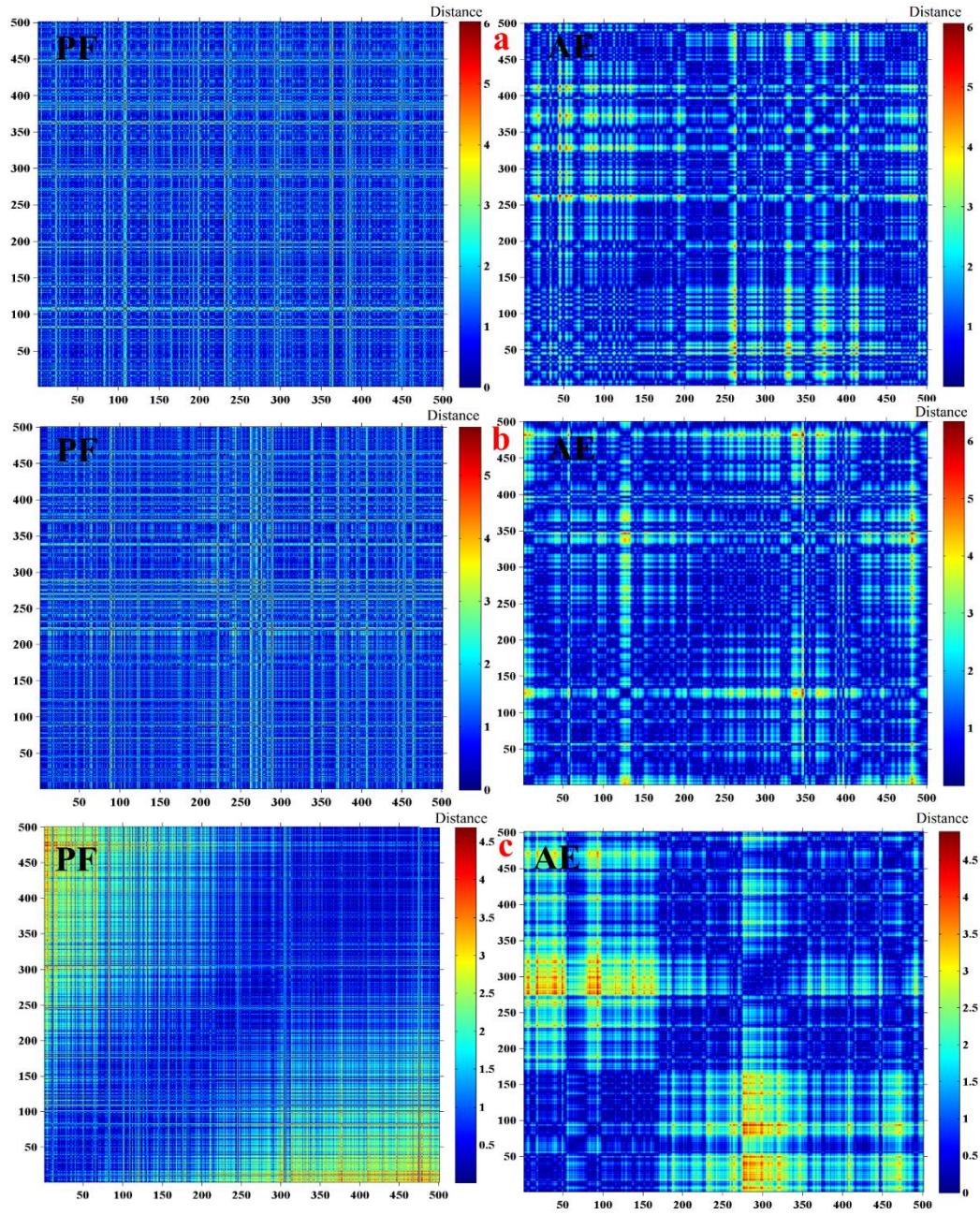


**Fig. 3.** UTRPs of PFs (left) and AE (right) signals at (a) dry bed, (b) after 0.5 mL and (c) after 1.5 mL of water injection ( $m = 3$ ,  $\tau = 4$ ).

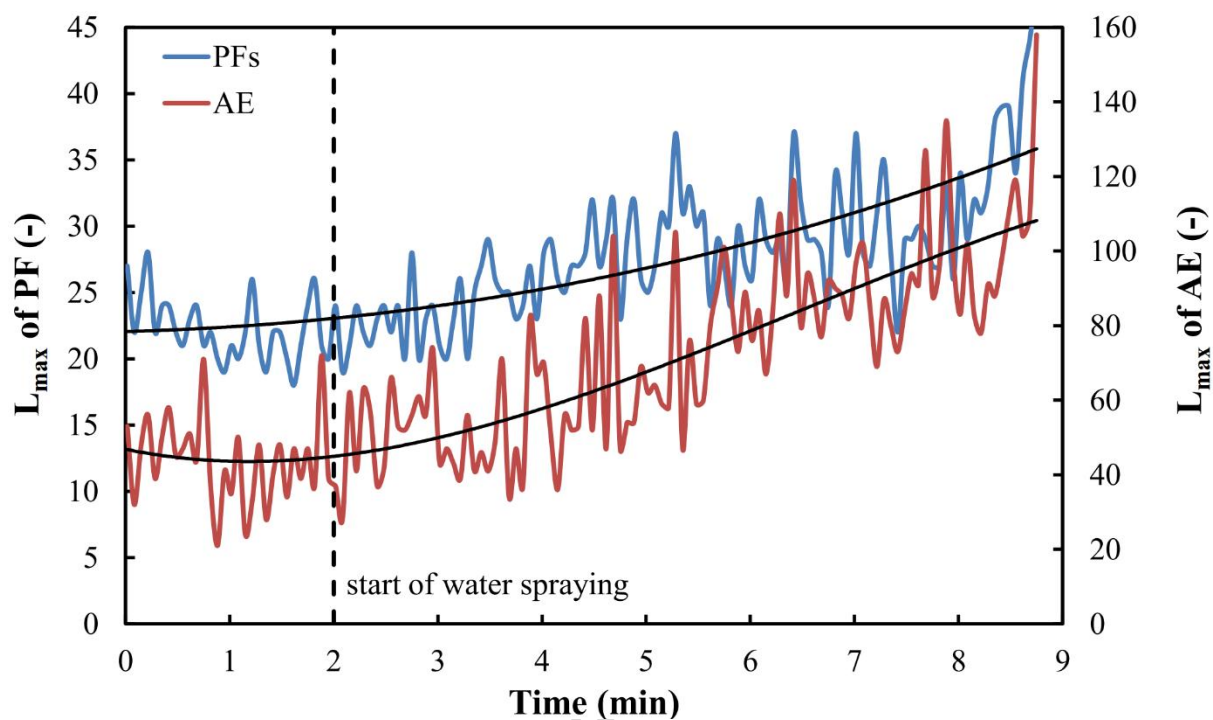




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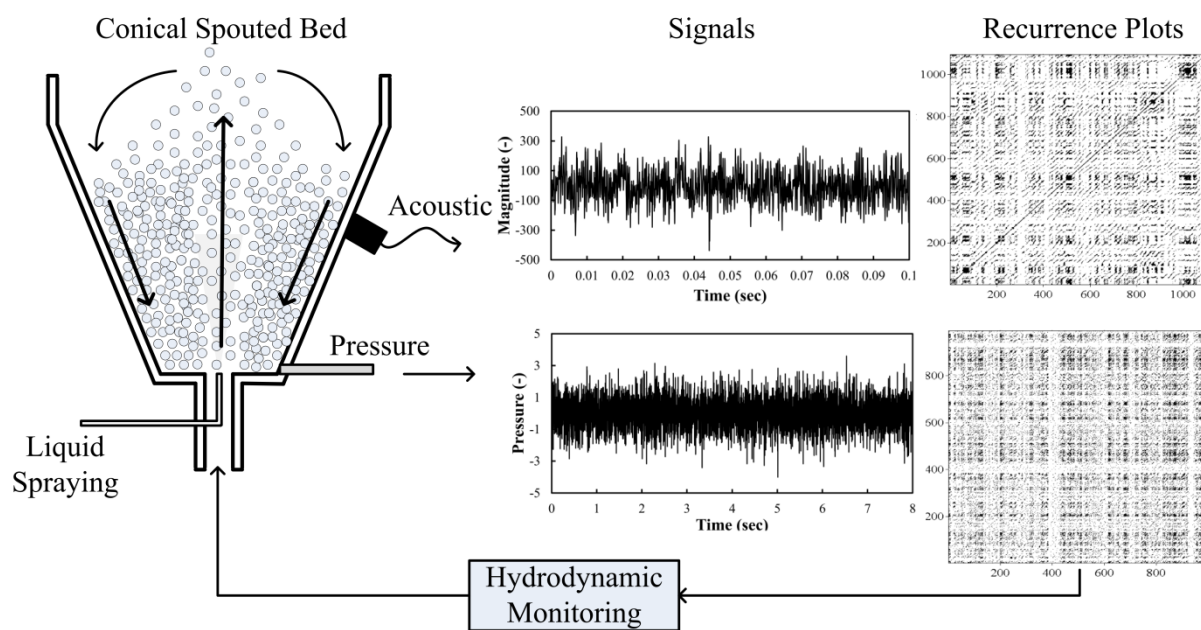
**Fig. 5.** Zoom of UTRPs of PFs (left) and AE (right) signals at (a) dry bed, (b) after 0.5 mL and (c) after 1.5 mL of water injection ( $m = 3$ ,  $\tau = 4$ ).



**Fig. 6.** Maximal length of diagonal line of the TRPs with time for PFs and AE signals.



# Graphical Abstract



### Highlights

- Nonlinear phenomena of a liquid sprayed conical spouted bed were investigated.
- Pressure fluctuations and acoustic emission signals were recorded and analyzed.
- Recurrence plot and recurrence quantification analyses of signals were presented.
- $L_{max}$  of recurrence plots increases by injection of the water into the bed.
- Hydrodynamic status of the bed becomes more deterministic with liquid injection.